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INSTRUMENTS TO MEASURE THE STRESS CONDITIONS EXISTING IN THE ROCKS SURROUNDING UNDERGROUND OPENINGS

by

A. N. May

Paper prepared for presentation to the International Strata Control Conference, Paris, France, on May 20, 1960, and published with the permission of the Director, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada

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November, 1959.

INSTRUMENTS TO MEASURE THE STRESS CONDITIONS EXISTING IN THE ROCKS SURROUNDING UNDERGROUND OPENINGS*

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ABSTRACT

This paper describes two instruments that have been developed at the Mines Branch to measure the stress in the interior of rocks surrounding underground openings. One instrument measures uniaxial stress changes and also allows the existing stress condition to be determined. The other measures biaxial stress changes.

The former unit has been sufficiently developed to allow it to be used in field investigations, but the latter is still undergoing laboratory development.

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INTRODUCTION

Measurement of the stress level existing in the interior of the ore body is a necessary part of any ground mechanics investigation associated with mining. As the stress level will vary within the ore body, it is not sufficient to measure the strains on a free boundary, and access must be made to the point where the value of the stress is required. This access is normally achieved by means of a drill hole.

The Mines Branch has spent many years of research on this problem of measuring stress changes that occur at the end of a drill hole, and the two instruments that are described in this paper stem from this continuing project.

The initial attempts in this field were mainly confined to inserting oil-filled rubber bags in the borehole, and to similar types of hydraulic units. These units, if in a highly deformable host material, gave a qualitative, though non-directional, picture of the stress changes taking place. The next stage in the development was a unit that would give the direction of the stress changes, although, once again, no reliable magnitude was obtained from them. This instrument consisted of a metal disc enclosed in a suitable housing and placed at right angles to the axis of the borehole. The magnitude and direction of the stresses in the disc were calculated from the readings obtained from a 3-45° element strain gauge mounted on it. This disc instrument was used in several field trials and, although a great advance from the rubber bag stage, had several disadvantages, the two major ones being insufficient mechanical strength and an inability

to relate accurately the stresses in the metal disc to those in the host material.

The two instruments that are described in this paper measure absolute values of stress changes, and also stress changes in a specified direction. The first unit that is described measures uniaxial stress changes; it is an electro-hydraulic instrument and is in current use in field investigations. The second unit measures biaxial stress changes, but is not yet sufficiently developed to be used in field investigations.

THEORETICAL PRINCIPLES INVOLVED IN THE DESIGN OF THE UNIAXIAL STRESSMETER

A great deal of effort has been devoted to the designing of instruments for measuring the stress levels at points remote from a free face. Previous efforts in this field had resulted in instruments that either recorded relative stress changes without being able to attribute any reliable magnitude to these readings, or recorded variations in the diameter of a drill hole. The latter method requires both a knowledge of the elastic constants of the material involved and a knowledge of the direction of the applied stresses.

A great advance in this type of instrumentation was made possible by Coutinho[1] when, in 1949, he demonstrated that under certain conditions the stress recorded by an instrument in intimate contact with the host material at the end of the drill hole bears a constant relation to the stress in the host material.

Consider an instrument placed at the end of a diamond drill hole and subjected to the stress fields as shown in Figure 1. Coutinho demonstrated that the relationship between the stresses in the host

material and those in the instrument can be expressed by:

$$\sigma_{11} = k_1 \sigma_{12} + k_2 \sigma_{22}$$

$$\sigma_{21} = k_2 \sigma_{12} + k_1 \sigma_{22}$$

where σ denotes stress. The first suffix denotes direction, the second the location of the stress. k_1 and k_2 are functions of the elastic constants involved.

Also, if k_1 and k_2 are plotted against $\frac{E_2}{E_1}$ (the ratio of the elastic moduli), plots as shown in Figure 2 are obtained. Two major points can be seen from these plots:

(I) If $\frac{E_2}{E_1} > 4$, then k_1 and k_2 approach a constant value.

(II) The values of k_1 and k_2 are relatively independent of Poisson's ratio (ν).

The significance of these two facts is that, if the ratio of the elastic moduli is greater than 4, the relation between the stress in the instrument and that in the host material is independent of the elastic constants of the host material in which the instrument is inserted. An instrument satisfying these conditions can then be regarded as measuring stress and as such is termed a stressmeter. The value of the elastic modulus for rocks encountered in mines is usually of the order of 0.5×10^6 to 2.0×10^6 psi. The effective modulus of the stressmeter was calculated to be in excess of 14×10^6 psi, thus satisfying the necessary criteria. This calculation was based upon a hypothetical stressmeter having a rectangular cross-section. While this simplification will introduce errors, it is felt to provide a

sufficiently close approximation to the actual value.

An advantage of this method where an accurate knowledge of the elastic constants is not required is the fact that rocks are anisotropic. If the usual uniaxial laboratory measurements are made, the values obtained may be far different to those applicable to the direction in which the field measurements were taken. In addition, it is often found that there is a difference between the values measured on samples in the laboratory and those measured in situ.

DESIGN OF THE UNIAXIAL STRESSMETER

An instrument utilizing the theoretical concepts which have just been outlined has been designed to measure the uniaxial stress changes that occur at the end of a diamond drill hole. Made of mild steel, with the active part 6 in. long and 2 in. in diameter, it is shown in the lower half of Figure 3, and a sectional view is given in Figure 4. The design and subsequent stages of development are given in greater detail elsewhere[2].

This stressmeter is constructed by axially splitting a steel rod part way along its length. In the main body A, a 1/100-in.-deep recess is machined and a diaphragm is welded on to cover this recess. The auxiliary body B is so machined that when it is rejoined to A the original shape of the rod is restored. The end of the rod is machined to form a head, and a hole is drilled connecting it to the recess. The recess is then filled with fluid, so that any pressure applied to the stressmeter will tend to displace the fluid into the head. The fluid then acts on a diaphragm screwed into the head and the strain induced in the diaphragm is proportional to the pressure applied to the

stressmeter. This strain is measured by means of a bonded resistance strain gauge.

To compensate for thermal effects and to minimize the effect of external lead resistance changes, dummy gauges are mounted on the body of the diaphragm unit. Two active and two compensating gauges are used, making it possible to connect the gauges to form a complete bridge network.

The arrangement shown in Figure 4 utilises a diaphragm unit, which screws into the body of the stressmeter, and an O-ring seal. In the earlier designs of the stressmeter the active diaphragm was silver-soldered into position and the compensating strain gauges were mounted on a disc located about the diaphragm. The main reasons for changing this design were: to improve temperature compensation, to obtain greater ease of maintenance, and to make the stressmeter adaptable to a wide range of stress values while retaining high sensitivity.

When the compensating gauges were mounted on a separate disc they were not subject to the same thermal conditions as the active gauges, due to the fact that the stressmeter acted as a heat sink for the diaphragm. With the present diaphragm unit the compensating strain gauges are mounted on the wall of the unit, thus giving improved temperature compensation.

To assist in maintaining long-term stability in the strain gauges, the maximum strain level that will be imposed upon them is restricted to 0.1%. This means that with a fixed diaphragm the stressmeter can only be used for a certain predetermined range of stress. This is inconvenient, and the advantage of the present design

is that diaphragm units of varying thickness can be strain gauged and one of appropriate sensitivity screwed into the stressmeter. These diaphragm units are very cheap and therefore a range of them can be stocked as shelf items. An assembled diaphragm unit is shown in Figure 5.

As the reliability of the stressmeter hinges on the stability of bonded strain gauges, an investigation was conducted into the long term stability of these gauges. Numerous combinations of gauges and cements were tested before the combination of a metal foil gauge and a thermo-setting cement (Armstrong X-27) was selected. The stressmeter is so designed that the strain gauge is never subjected to a strain in excess of 0.1% Up to this limit the investigation showed that the bonded resistance strain gauge is a reliable sensing unit for long term work.

In order to secure this stability it is essential to protect the gauges from all moisture. This is achieved by screwing into the head a cap fitted with a waterproof gland for the four-conductor cable. As an added protection against moisture the head is packed with silicone grease. The waterproof gland is simple, but very effective. A copper tube is sweated into the exit hole, the cable is fed through the tube, and the tube is then crimped about the cable.*

When the stressmeter is being installed it is regarded as essential that it be pre-stressed, for the following reasons:

(a) To ensure that an intimate contact has been established between the stressmeter and the host rock.

(b) To be able to measure decrease in stress.

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* This method was first brought to the attention of the author by Mr. W.L. Gibson, of the Ontario Hydro-Electric Power Commission, Toronto, Ontario.

(c) To reduce to a minimum the amount of grouting between the stressmeter and the host rock.

A series of experimental runs, with the stressmeter prestressed into a concrete block to varying stress levels, was carried out. It was found that if the level of prestressing exceeded 100 psi, the relation between the applied stress and the stress recorded by the stressmeter was independent of the prestressing applied. If it is anticipated that the stressmeter will be experiencing a decrease in stress, then the prestress level must obviously exceed this anticipated decrease.

The prestressing is achieved by making the stressmeter with a 1° taper on the sides and by lining the end of the borehole with a pair of steel sleeves which have a matching internal 1° taper. By driving the stressmeter into these sleeves the requisite amount of prestressing can be obtained. The stressmeter is shown in position within these sleeves in Figure 4.

The two sleeves are bonded together with a strip of rubber between the two halves. This allows the sleeves to adjust themselves to the size of the drill hole and prevents the grouting from flowing between the sleeves. The two halves, assembled, are shown in the upper half of Figure 3.

ASSOCIATED RECORDING INSTRUMENTATION

The output from the stressmeter is measured by means of a transistorized bridge unit, which is a modification of the Baldwin SR-4. The low operating voltages of the transistor have made it possible to

modify this bridge sufficiently for it to be certified as intrinsically safe for use in mines subject to an explosive atmosphere. This bridge will record stress changes in the stressmeter with an error of less than ± 5 psi. It is an easily portable unit, weighing only 10 lb.

The limitation with this type of instrument is that it can only be used for spot readings and consequently a great deal of information is lost. To achieve maximum value from any underground instrumentation, continuous recording is essential.

In a mine where there are no electrical restrictions, continuous recording does not present any major problems. A commercially available, multi-channel automatic potentiometer recorder with a 0-5 mv range, in conjunction with a balancing unit and suitably regulated power supplies, is found to work excellently.

The balance position is obtained by shunting a fixed resistor and potentiometer across one arm of the strain gauge bridge circuit. With this arrangement, errors due to any instability in the potentiometer will be reduced to a minimum. The function of the fixed resistor is merely to prevent the arm from being shorted out. A switching arrangement is provided to enable the appropriate arm of the bridge to be selected.

The leads from the stressmeters plug into this panel through a 4-pin plug. The SR-4 bridge has been adapted to provide a socket for this plug so that readings on the recorder may be checked against readings on the bridge.

Where there are restrictions on the use of electrical equipment, continuous recording becomes a more difficult problem, as no commercially available recorders are suitable. A recorder is now under

development in the Mines Branch laboratories for use under these conditions.

TESTS CARRIED OUT ON THE STRESSMETER

The validity of Coutinho's theoretical work was checked experimentally by him and has been checked subsequently by others. Hence, no attempt was made to undertake a rigorous experimental verification of the theory. However, during the course of developing the instrument numerous runs were carried out with the stressmeter located in blocks of material which have different elastic constants, and when optimum conditions existed it was found that the stressmeter would record absolute values of stress with an error of less than 12%.

The two major factors to be considered in order to obtain these optimum conditions are: the uniformity of stress distribution throughout the block, and the thickness of the grouting around the stressmeter sleeves.

To improve the uniformity of the stress distribution, the bearing surfaces are capped with sulphur. Where it was suspected that anomalous results were being obtained due to non-uniform stress distribution, the strains on the surfaces of the block were measured.

As the elastic modulus of the grouting is very low, compared with that of the stressmeter, the thickness of the grouting has a pronounced effect on the stressmeter readings and consequently must be reduced to a minimum. If the grouting is 1/16 in. in thickness, it can be shown that the readings will be 50% less than the readings obtained if intimate contact with the host material was possible without the use of grouting.

The thickness of the grouting is, of course, influenced by the irregularities in the walls of the drill hole, so that particular attention must be paid to the drilling and reaming of the hole.

To enable the output from the stressmeter strain gauge bridge circuit to be related to the applied stress, the stressmeter and sleeves were subjected to a uniaxial load and a calibration curve of stress versus strain gauge output was obtained.

The experimental runs were carried out with the stressmeter located in a hole drilled right through a concrete block. The concrete blocks were 9 in. by 12 in. by 12 in. When the stressmeter was installed, the concrete block was loaded in a testing machine and the stressmeter was read, by means of a Baldwin bridge, at regular increments of load. Plots showing the stress values recorded by the stressmeter, against the stress applied to blocks of different elastic constant, are shown in Figure 6. The former value is obtained from the calibration curve for the stressmeter.

It can be seen from Figure 6 that when the stressmeter is placed in a block of approximately the same elastic modulus, 12×10^6 psi, the stress relationship approaches a 1:1 ratio. The other results shown are for materials where the ratio of the elastic constants, $\frac{E_2}{E_1}$, is greater than 4. While there is a spread in the results, the maximum departure from the theoretical value is only 12%.

As the stressmeters are used in investigations lasting several months, they are of doubtful value unless high stability can be achieved. This aspect was investigated in the laboratory by subjecting the stressmeters to dead weight loading and observing the readings over a period of weeks. This test showed that it was possible to obtain a stability equivalent to ±20 psi. Prior to use in the field,

stressmeters undergo a stability test for two weeks; those exhibiting a drift in excess of this ± 20 psi value are rejected.

The next stage of the investigation was to see whether this stability could be achieved under actual mining conditions. Consequently, it was decided to install two stressmeters in a nearby mine. This field test also provided an opportunity to try out the stressmeter installation technique that had been developed in the laboratory.

The mine selected was that of Canadian Refractories Limited at Kilmar, Quebec. This mine offered several advantages, including close proximity to the laboratory, extremely damp conditions, and, very important in this work, an extremely cooperative management. The results of this trial and of subsequent investigations involving the stressmeter confirmed that the high stability obtained in the laboratory could be reproduced in the field. The Kilmar trial is reported in greater detail elsewhere[3].

INSTALLATION TECHNIQUE

An attempt to simulate field conditions in the laboratory was made, locating the stressmeter in a block of concrete at the end of a 20 ft length of pipe. When the technique was felt to be satisfactory it was tried out in the Kilmar mine. With very minor modifications it was found to function perfectly.

In order to force the stressmeter into the sleeves, a long-stroke, hollow-bodied ram was designed which could be attached to the sleeves and then be detached after the requisite amount of prestressing had been obtained. A plastic steel grouting was used to take up any irregularities that existed between the sleeves and the side of the

borehole. This method of installation reduces the thickness of the grouting to a minimum, so that the relatively low elastic modulus of the grouting (0.8×10^6 psi) has a negligible effect on the theoretical concepts involved. The following procedure is then adopted:

(I) A hole is drilled with a BX diamond bit (2.330 in. diam.) and body reamer to the requisite position.

(II) The grouting is placed at the bottom of the hole.

(III) The stressmeter, sleeves and hydraulic ram, in one complete unit, are pushed down the borehole. The rods used for this purpose are marked to allow the stressmeter to be correctly oriented in the hole.

(IV) Pressure is applied to the end of the rods, forcing the grouting to flow around the sleeves.

(V) The stressmeter is coupled to the strain gauge bridge and a balance position is obtained.

(VI) A hydraulic jack is operated to actuate the hollow ram and drive the stressmeter into the sleeves. This operation is continued until the requisite amount of prestressing is indicated on the bridge.

(VII) The pressure is then released on the jack and the ram is disengaged from the sleeves and withdrawn from the borehole.

(VIII) The conduit is slipped over the cable and screwed onto the back of the stressmeter.

DETERMINATION OF THE EXISTING STRESS WITH THE STRESSMETER

The stressmeter, when installed at the end of the borehole, only records stress changes that occur after its installation. The stress condition at the time of the installation is of prime importance in any investigation, and must be known.

These initial stress conditions are often calculated by assuming the weight of the overburden to be the only source of applied stress. Such calculations, however, often prove to be erroneous, particularly in areas that have been subjected to geological disturbances; for example, horizontal components of stress far in excess of those due to Poisson's effect are often encountered[4] [5].

Hence it is felt that the existing stress condition must be measured. This can be achieved by prestressing the stressmeter to a value higher than is thought to be the existing stress level. If the stress is then relieved from around the stressmeter, by trepanning, the difference in the indicated values of stress before and after the trepanning operation will be the existing stress.

Consider the very simple uniaxial stress condition. If σ_{11} is the residual stress in the host material and σ_{21} and $\sigma_{21'}$ are the values of stress before and after trepanning, then

$$\sigma_{11} = k_1 (\sigma_{21} - \sigma_{21'})$$

A more complicated stress field will necessitate the use of three stressmeters in the one borehole.

FIELD INVESTIGATION INVOLVING THE USE OF THE STRESSMETER

A ground mechanics investigation is being conducted in a submarine iron-ore mining operation. The ore lies in three parallel beds which outcrop on land and then pitch 8° under the sea. The mining

is a room-and-pillar type operation, and in the area under examination the pillars are 25 ft x 125 ft in area, 18 ft high, and the cover is composed of 800 ft of strata and 200 ft of water. From 50 to 60% of the ore is being extracted.

The current purpose of the investigation is to ascertain the distribution of stress that takes place after extraction of the ore, the ultimate aim being to solve the vexing problem of what size of pillar and span of roof to use in order to obtain the most economic extraction of the ore. In order to put the stressmeter into its proper perspective in this field trial, it is proposed to list briefly, below, the parameters that are being measured (when mining practice allows):

(I) The stress changes in the interior of the pillars - utilizing the stressmeters.

(II) The strains induced in the roof.

(III) The penetration of the pillar into the roof and floor.

(IV) The compression of the pillars.

(V) The presence of cracks and fissures in the pillars - utilizing a sonic technique.

In addition, core samples are obtained from the roof, floor and pillar to allow Young's Modulus and Poisson's Ratio to be determined for compressive uniaxial loading.

Since the field investigation was initiated four months ago, there has been very little advance in the line of extraction. Mining has been mainly restricted to removing 6 ft of ore left behind on the roof. Consequently, the only information that has been yielded by the stressmeters to date relates to their stability. Their stability has been

shown to be quite satisfactory over this period of time. The results obtained from the four stressmeters that were installed when the program was initiated are shown in Figure 7. It can be seen that there is only slight activity due to the mining.

During this field trial it was found possible to have an unskilled operator, following a very brief period of instruction, install these stressmeters and take the subsequent readings.

A DESCRIPTION OF THE UNIT FOR MEASURING BIAXIAL STRESS

A logical development from the measurement of uniaxial stress changes is the measurement of biaxial stress changes. Accordingly, a theoretical study was undertaken to assess the possible application of a hollow cylindrical inclusion[6].

Based on a mathematical solution by Hiramatsu, Kiwa and Oka[7], a simple expression was derived relating $U_{r.\theta}$, the radial deformation in the direction θ, and the two principal stresses p and q. The stress field applied is shown in Figure 8. The derived expression is:

$$U_{r.\theta} = K_1 (p + q) + K_2 (q - p) \cos 2\theta,$$

where K_1 and K_2 are functions of the elastic constants of the hollow inclusion and of the host material. The initial aim of the study was to derive a design criterion analogous to the one postulated by Coutinho for the solid inclusion. For this to occur, K_1 and K_2 must approach constant values.

To investigate this criterion for a given value of n (ratio of ID to OD), K_1 and K_2 were calculated for values of the elastic modulus of the host rock varying from 0.5×10^6 to 10×10^6 psi. Within

the range of values considered, K_1 was reasonably constant but K_2 showed no tendency to approach a constant value. A typical set of values is shown for n = 1.69 in Figure 8. This is the value of n of the cylinder used in the laboratory tests.

In order to check the theoretical work, a hollow steel cylinder of outside diameter 3 in. and internal diameter 1.77 in. was grouted in a concrete block. The variation in the internal diameter of the cylinder was measured with an air gauge, which measured to within 5 micro-inches. The air gauge has a range of movement of only 450 micro-inches. This entailed setting the measuring head in the cylinder to within 1/10,000 in. This setting was achieved by machining a shallow keyway in the cylinder with an accuracy of 1/1000 in., and the final adjustment was accomplished by hand-lapping the measuring head, mounting it in the cylinder, and activating the air gauge, repeating these steps until the desired setting on the gauge was obtained.

It is fully appreciated that there are numerous other ways of measuring the variation in internal diameter, that are probably superior to the air gauge, but this technique was used for a specific reason, namely, that a number of investigations into the stress distribution occurring around underground openings are carried out in coal mines and other places where the explosive atmosphere severely curtails the use of electrical equipment. Under these conditions, it is felt that the air gauge has many possible applications, and this investigation provided a valuable opportunity to familiarize the research group with the technique.

Figure 9 shows the results obtained when the concrete block, with the cylinder grouted into it (shown in Figure 10), was loaded

perpendicular to and in the same direction as the measuring head. Values were obtained for the elastic constants of the concrete, and the theoretical values for $U_{r,\theta}$ were calculated. The calculated values are shown plotted alongside the experimental values.

Although it was not possible to regard this hollow inclusion as a stressmeter in the same way as the uniaxial instrument, if the elastic constants of the host material are known the magnitude of the two principal stresses can be calculated from the variations in the internal diameter.

CONCLUSION

This paper has described two instruments that have been developed to measure the stress condition that exists within the interior of an ore body. One instrument, which is referred to as the uniaxial stressmeter, will measure uniaxial stress changes, in absolute units, that take place at the end of a borehole. This instrument is in use in a current field trial, and both the method of installing and the stability of the instrument under actual mining conditions have been found to be satisfactory.

A method is also outlined whereby the existing stress condition can be determined with a stress relaxation technique, using three stressmeters in the one borehole. At the time of writing this paper, the method has yet to be tried in the field.

The other instrument has been designed to measure biaxial stress changes. Initial laboratory investigations are very encouraging, but considerably more development work is necessary before the instrument can be considered suitable for use in the field.

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Fuels Division,
Ottawa, November 12, 1959.

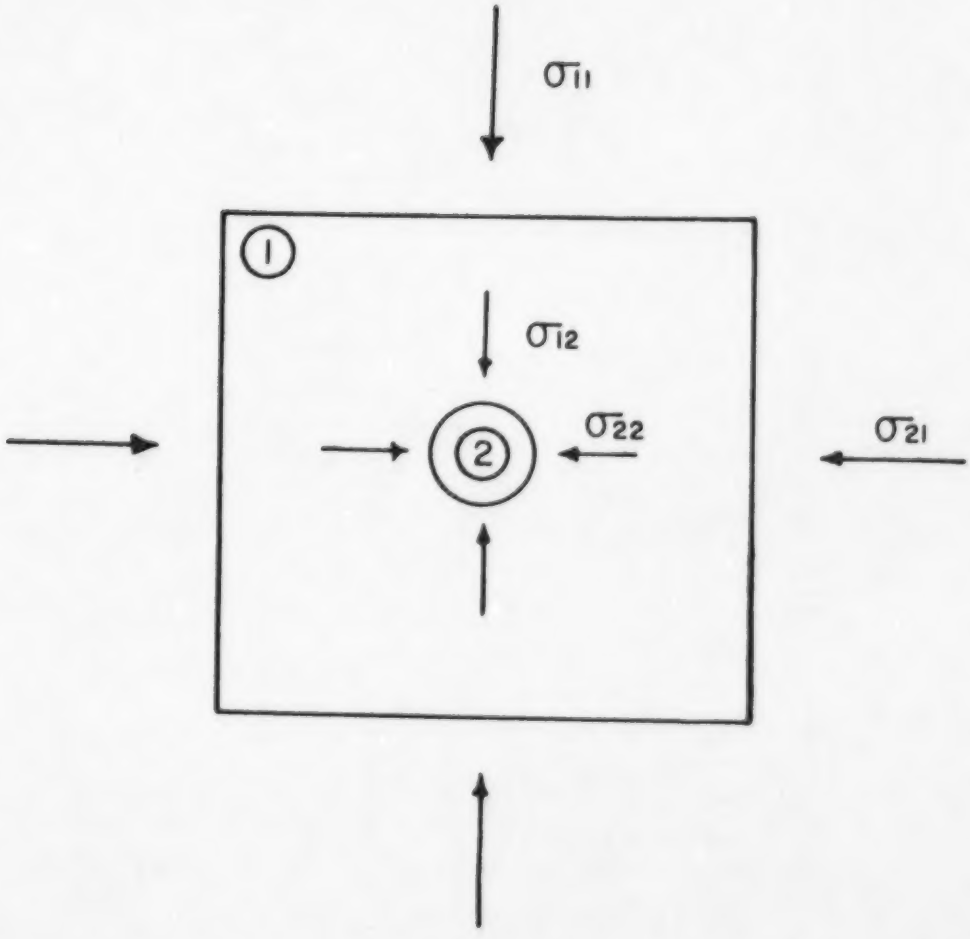

Figure 1 - Stress distribution around the inclusion

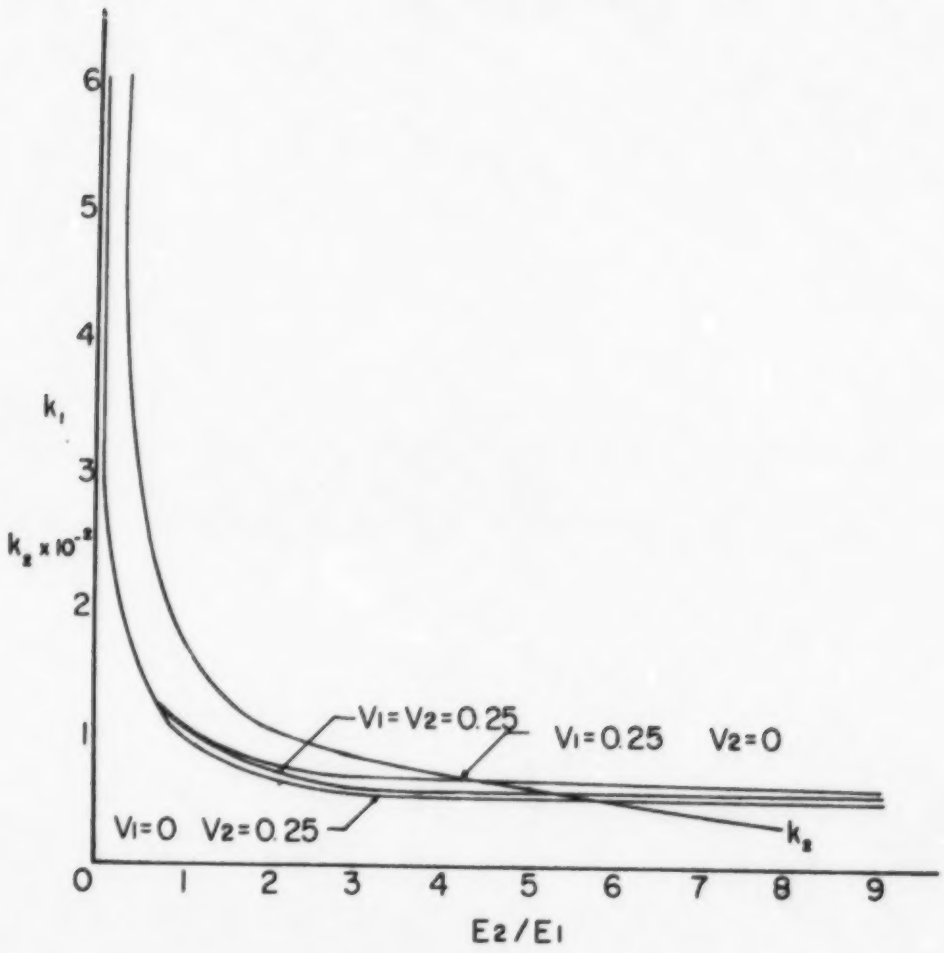

Figure 2 - Plot of $\frac{E_2}{E_1}$ against k_1 and k_2

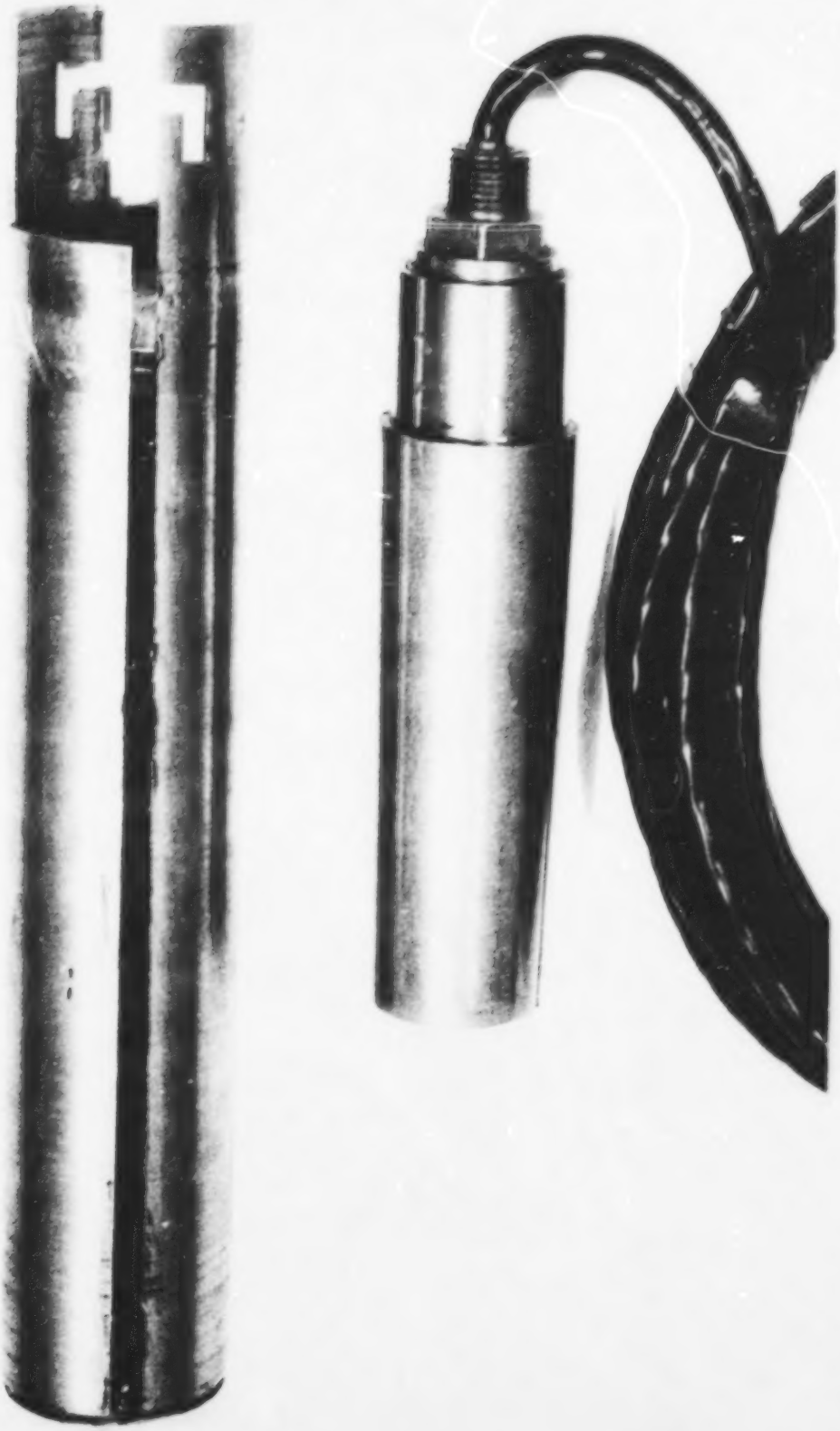

Figure 3 - Uniaxial stressmeter and sleeves

UNIAXIAL STRESSMETER

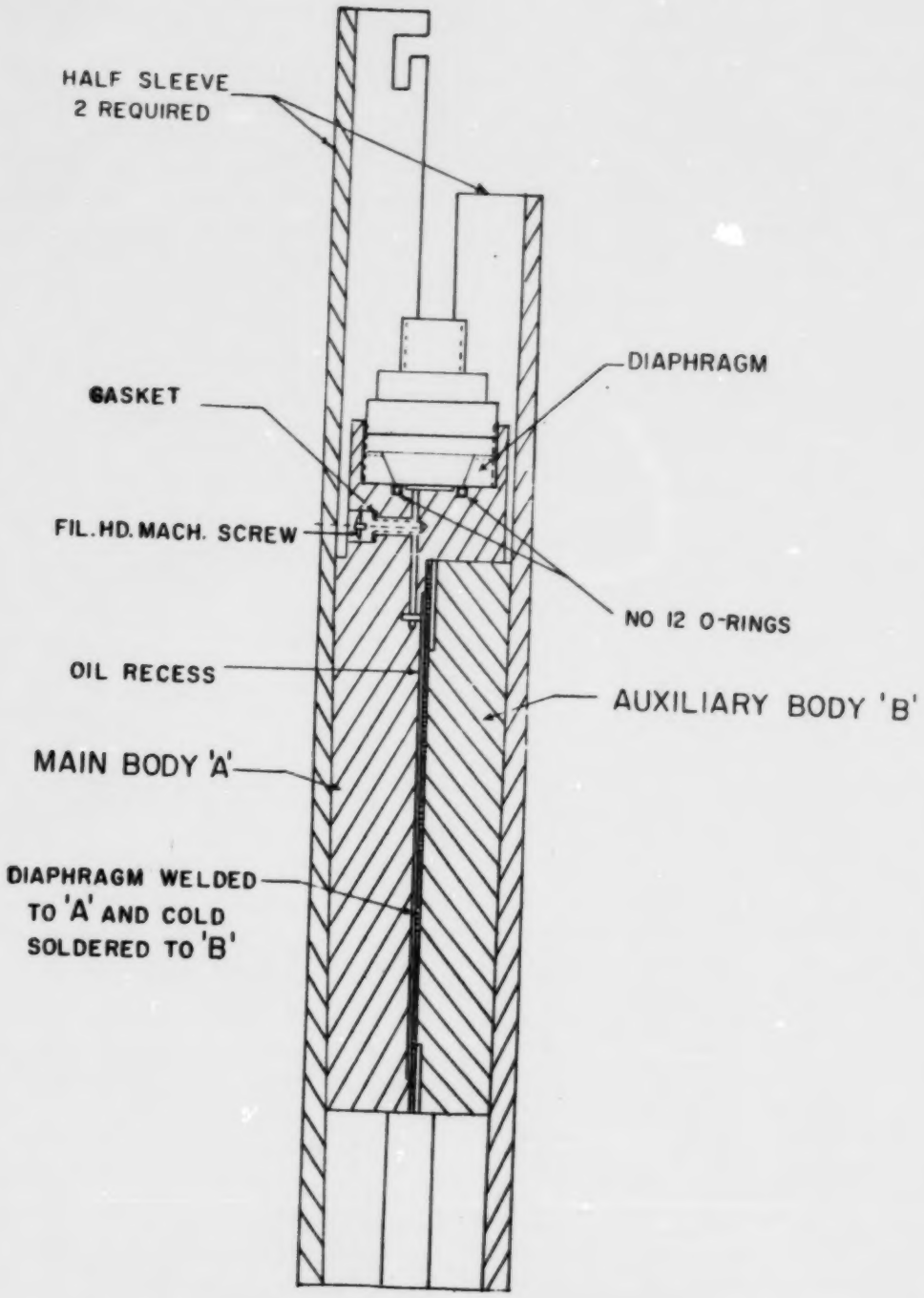

Figure 4 - Sectional drawing of stressmeter

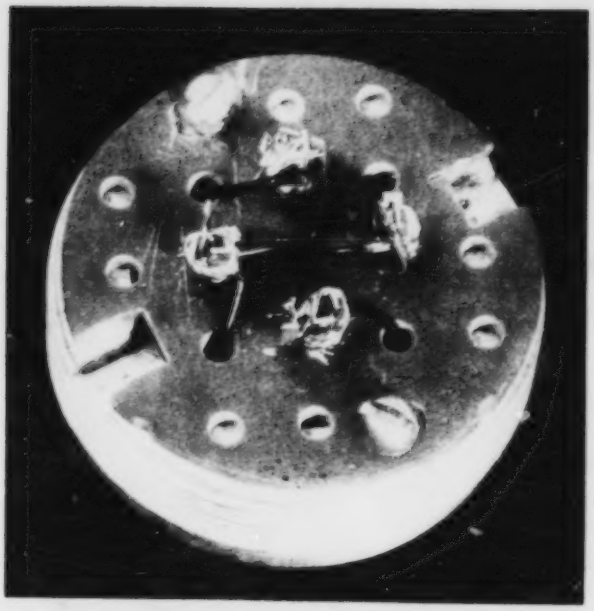

Figure 5 - Assembled diaphragm unit

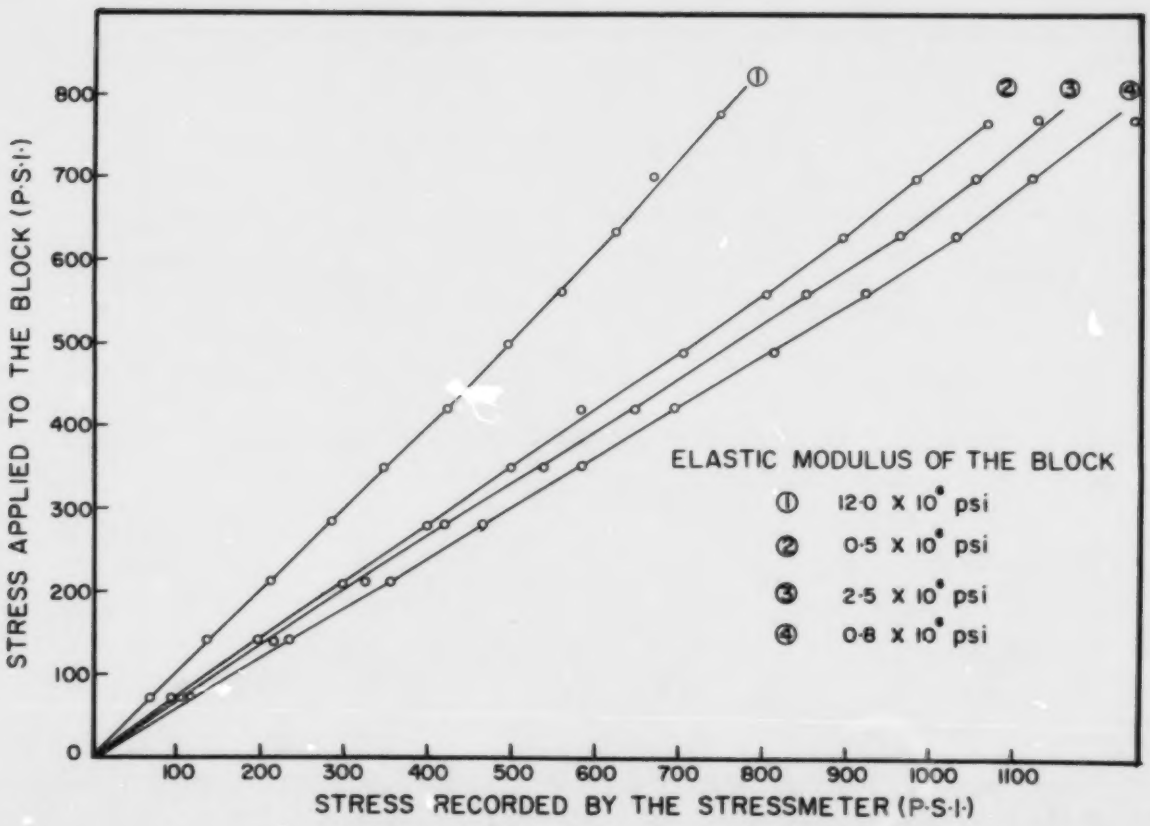

Figure 6 - Stress recorded by the stressmeter against the stress applied to the host block

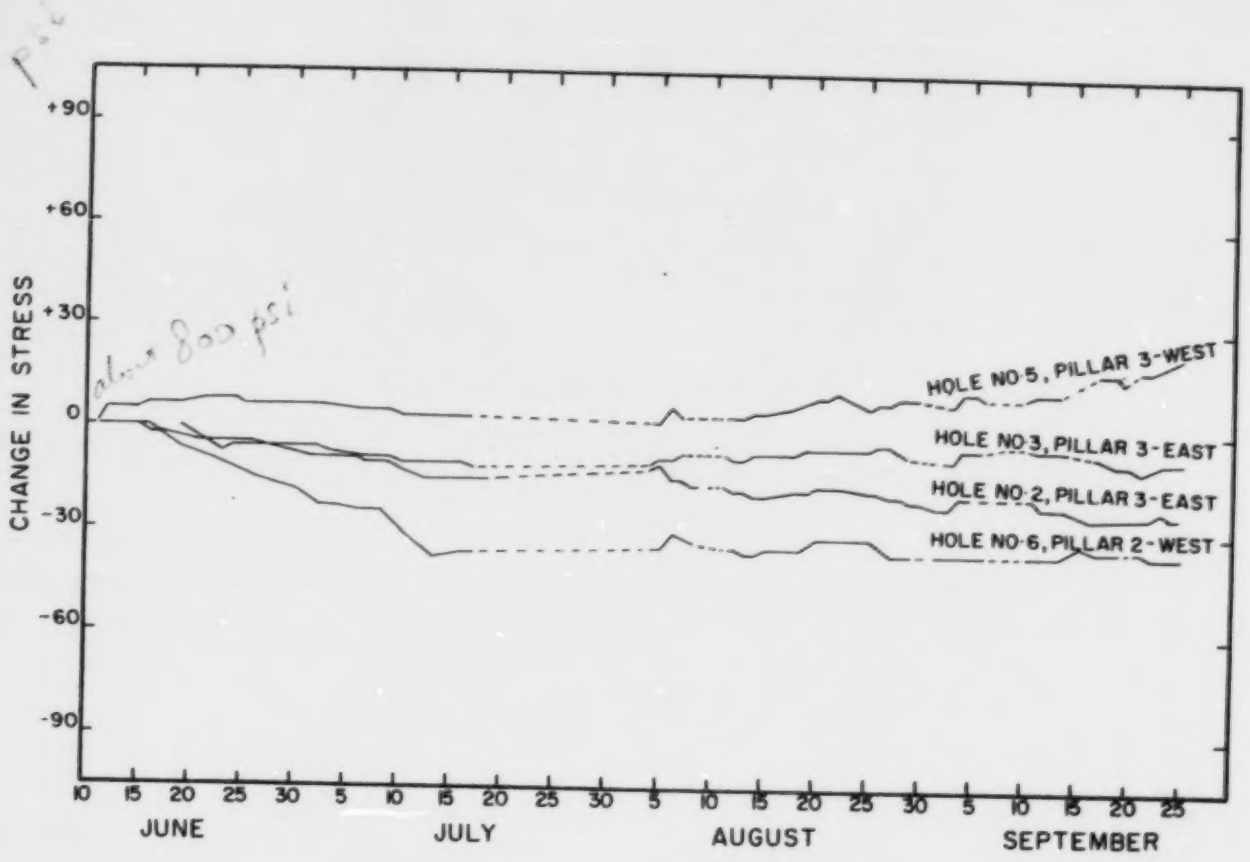

Figure 7 - Field results obtained with the stressmeter

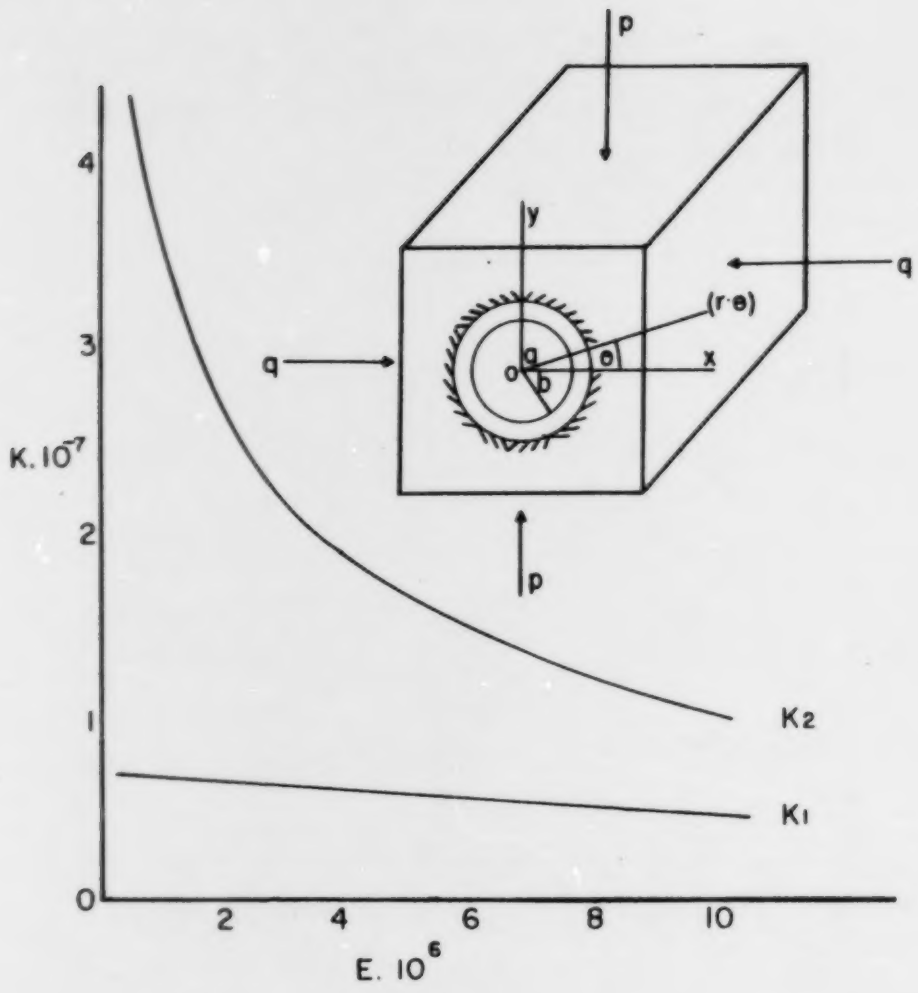

Figure 8 - Plot of K_1 and K_2 against E

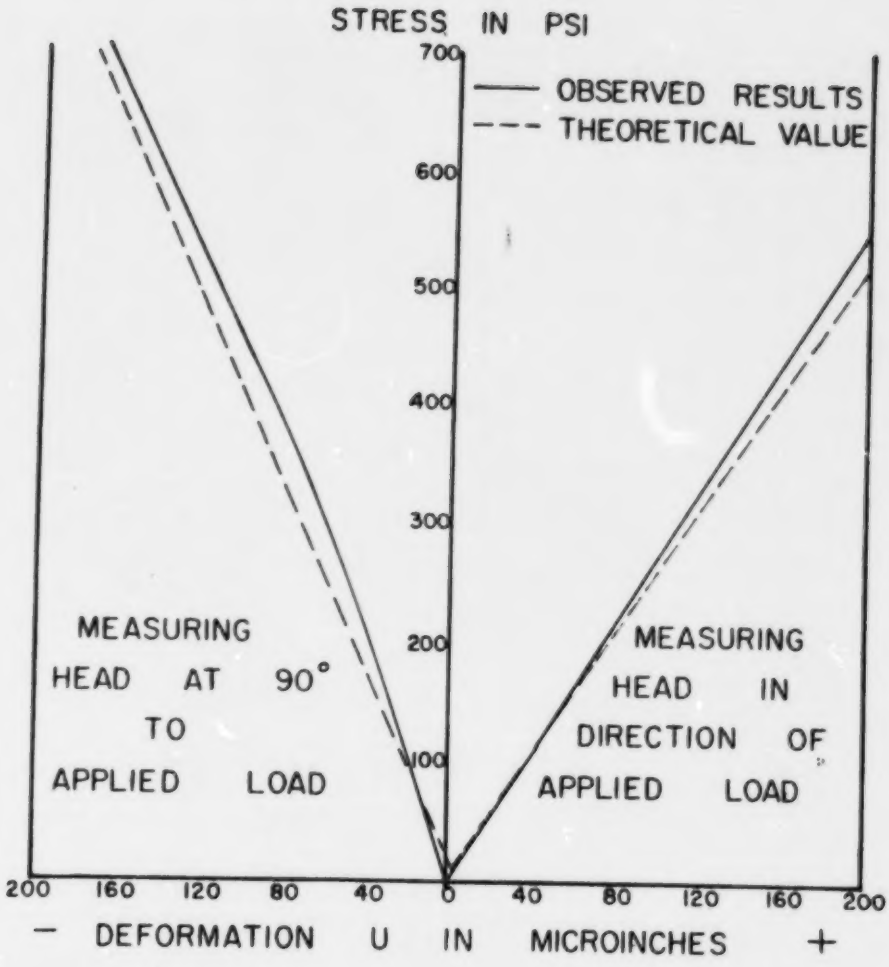

Figure 9 - Stress applied to the host block against diametral change in the cylinder

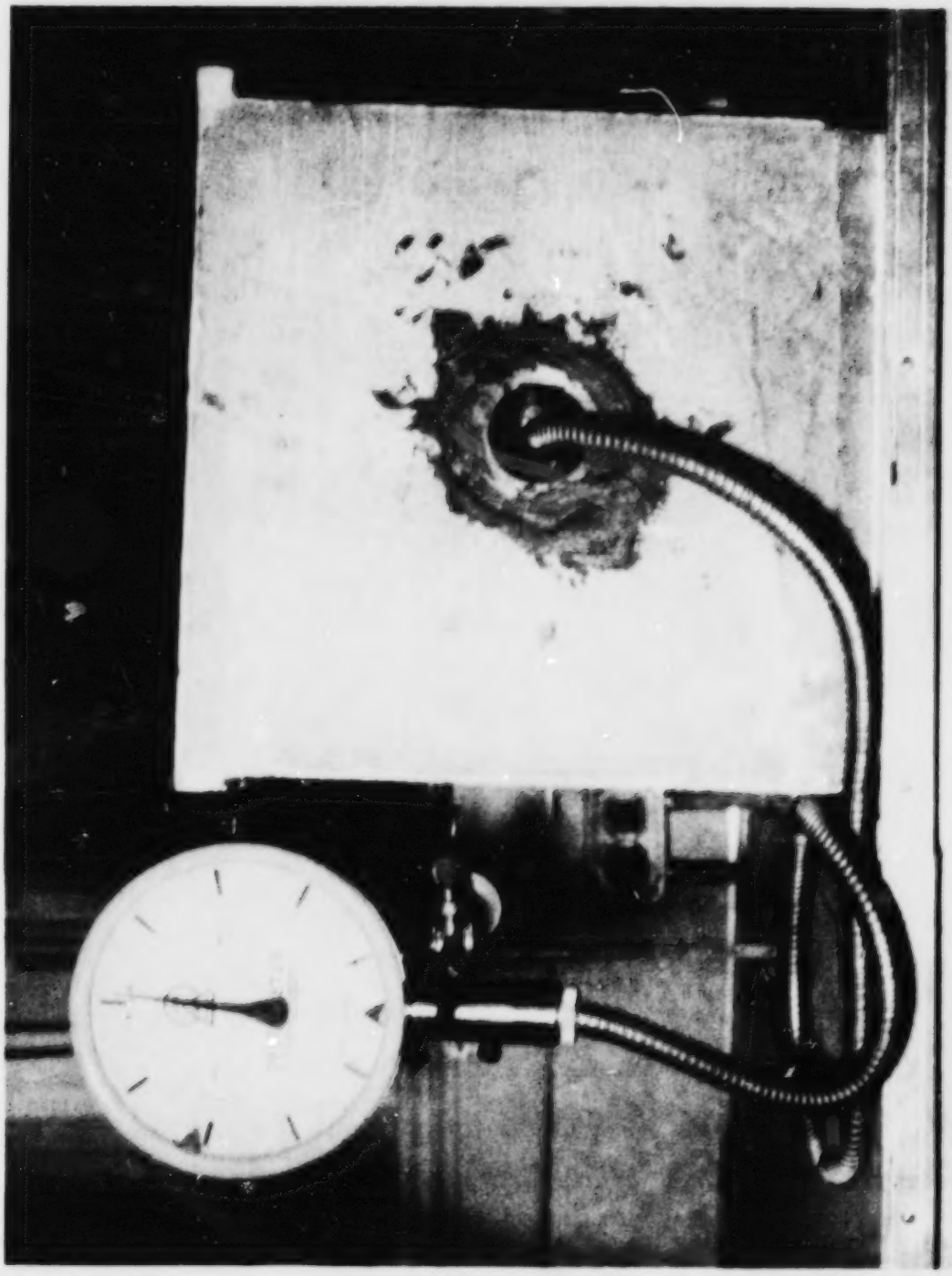

Figure 10 - Biaxial unit in concrete block